Development of Active Control Strategies for Wind Farms

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Introduction

Wind turbines operate to maximize their own performance without considering the impact of wake effects on nearby turbines. There is potential to increase total power output by coordinating individual turbines in a wind farm accordingly. Design and analysis of such coordinated controllers requires wake models of adequate accuracy but low computational complexity. The focus of this study was on developing insight for control methods for optimization of turbine arrays using simple wake models.

Materials and Methods

The wake model used is similar to the *Park model* [1], based on the assumption that the wake diameter (D) expands linearly with the distance behind the turbine. The interaction between wakes assumes linear superposition, and the velocity deficit ($\delta V_i(x, a_i)$) of the wind behind each turbine is a function of the induction factor (a), and distance (x) behind the previous turbine. The deficits stack according to the following equation

$$V_i(a, x) = V_\infty \left(1 - 2\sqrt{\sum_{j=1}^{i-1} (a_j c_{ji}(x))^2}\right) \quad (1)$$

where V_∞ is the free stream velocity,

$$c_{ji}(x) = \left(\frac{D_i}{D_i + 2k(x_i - x_j)}\right)^2 \frac{A(x)}{A} \quad (2)$$

and k is the wake decay constant. Power extracted by turbine i is given by:

$$P(a_i, V_i) = \frac{1}{2}\rho A V_i^3 C_p \quad (3)$$

where $C_p(a_i) = 4a_i(1 - a_i)^2$ is the power coefficient.

Virtual Wind Simulator (VWiS) code created by the Saint Anthony Falls Laboratory (SAFL) was used to evaluate the accuracy of the power output predicted by the Park model [2]. Optimal induction factors calculated by the Park model were implemented in VWiS and the power output with these induction factors were compared.

Conclusion

The Park model does not capture the complex dynamics of wakes between turbines accurately. It does however provide valuable insight into this interaction, and shows that running the front turbines sub-optimally, may increase the power output of the system as a whole. The optimal induction factors of turbines at various spacing was found to be non-trivial. The power predicted by the Park model is significantly higher when compared to VWiS, suggesting the model may need to be modified to match the results of the high-fidelity simulations.

References

[1] N.O.Jensen, *A note on wind generator interaction*, Tech.Rep.Risø- M-2411, Risø, 1983.

[2] Yang, X., Sotiropoulos, F., Conzemius, R. J., Wachtler, J. N., Strong, M. B., *Large-eddy simulation of turbulent flow past wind turbines/farms: the Virtual Wind Simulator (VWiS)*, Wiley Online Library, 2014

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Results - Low Fidelity Model

The efficiency of a wind farm is adversely affected by wakes generated from upstream turbines. The image in Figure 1 shows the 5-turbine array used in this analysis. The equal spacing between turbines was varied from 3 to 5 diameters downstream (3D - 5D), and optimal induction factors were calculated.

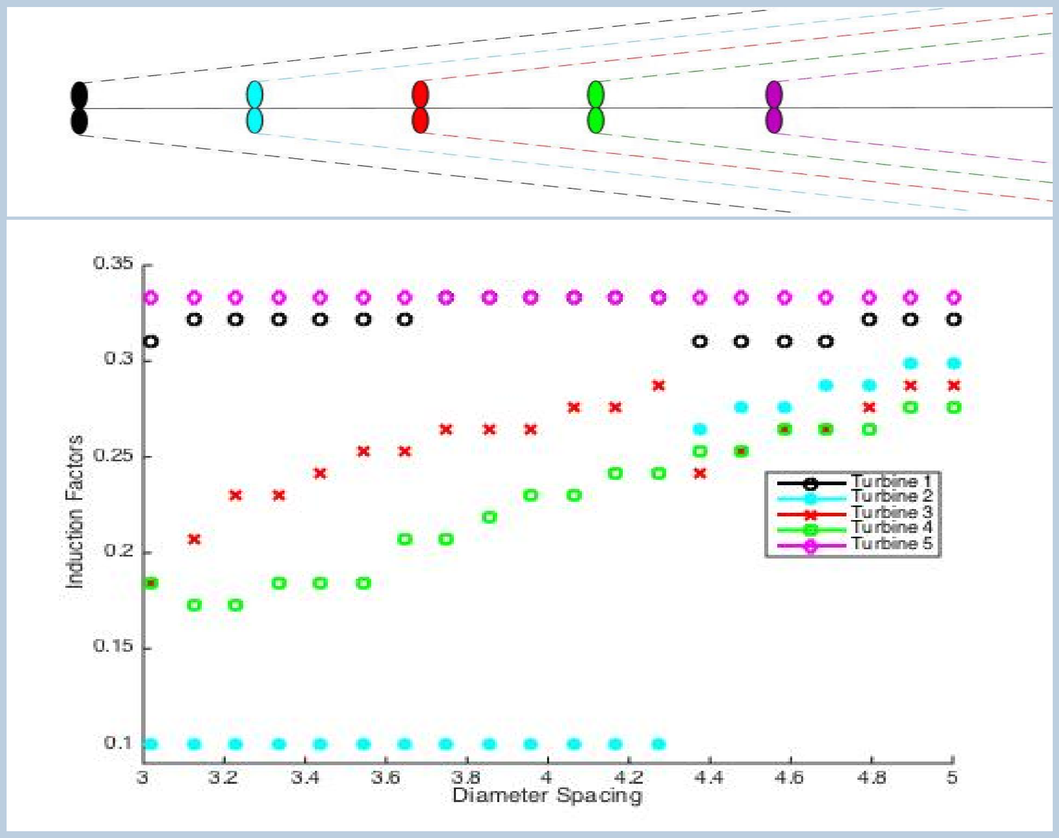

Figure 1: Simple 5-turbine arrangement of wind farm analyzed. (top); Optimal induction factors versus spacing between turbines (bottom).

As seen in Figure 1, the optimal induction factors of the turbines vary nontrivially with spacing. The last turbine in the array always has a maximum induction factor of ($a_{max} = 1/3$). The deficit caused by turbine 2 plays a crucial role in the power of the system; for optimal power, it has an induction factor of 0.1, which means it is effectively turned off at spacings below about 4.3D. Turbines 1, 3 and 4 also must be reduced to optimize the power output. As the distance between turbines increases, the induction factors approach a_{max}, as expected.

Results - High Fidelity Comparison

Optimal induction factors determined by the Park model were implemented into VWiS for various spacings between 4 and 5 diameters; the power outputs in each case were then compared to determine the accuracy of the Park model's results.

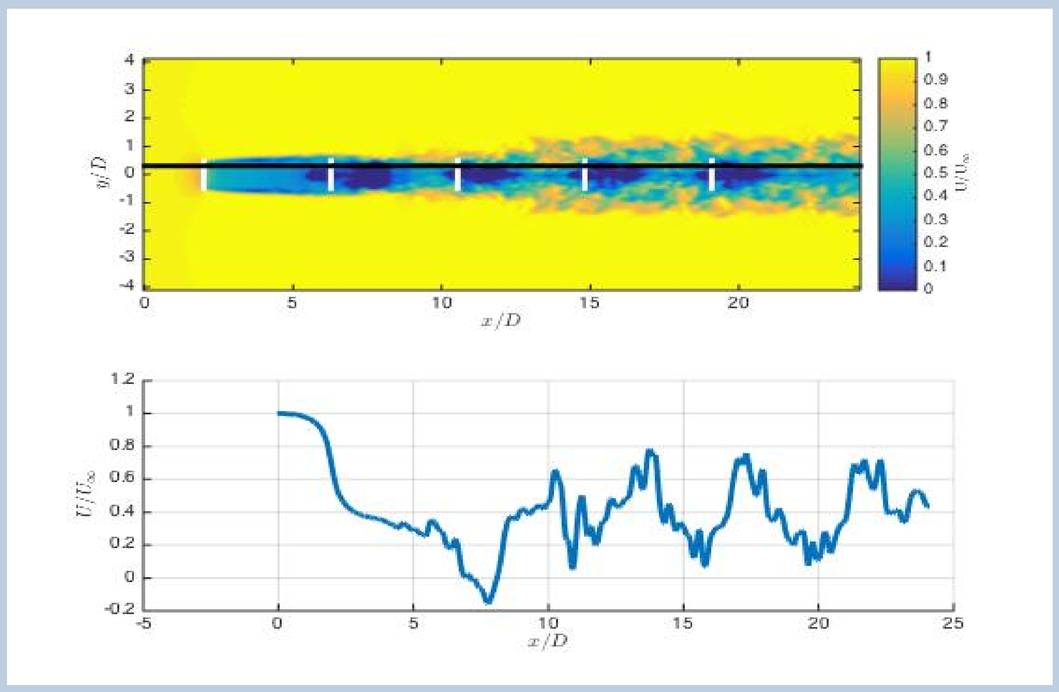

Figure 2: Streamwise velocity profile of 5-turbine array analyzed using VWiS (top). The velocity in the wake at half radius (horizontal black line in velocity profile) is plotted versus distance (bottom).

The velocity profile and power predicted by the Park model were significantly higher than those determined using VWiS. This was expected, as the Park model ignores the complicated dynamics of the system. In certain cases however, the high fidelity model agreed with the Park model's trend of the power captured; that power of the system as a whole may be increased when running several turbines in the front sub-optimally.